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Authors(s)	Alshehri, Fawaz, Kenny, Paul, Pinheiro, Sérgio V., Ali, Usman, O'Donnell, James
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DEVELOPMENT OF A MODEL VIEW DEFINITION (MVD) FOR THERMAL COMFORT ANALYSES IN COMMERCIAL BUILDINGS USING BIM AND ENERGYPLUS

Fawaz Alshehri[1], Paul Kenny[2], Sergio Pinheiro[1], Usman Ali[1] and James O'Donnell[1]

[1] *School of Mechanical and Materials Engineering, UCD Energy Institute, University College Dublin, Ireland.*

[2] *School of Architecture, Planning and Environmental Policy, University College Dublin, Ireland.*

E-mail: Fawaz.alshehri@ucdconnect.ie

Abstract–Buildings are major consumers of global energy resources. Approximately 80% of the energy used in commercial office spaces, is typically used for maintaining optimal comfort levels through delivery of heating, cooling, ventilating, and lighting. Building Information Modelling (BIM) has seen a significant up-take by designers in pursuit of sustainable building designs. Furthermore, general BIM systems already contain much of the information that can be further reused for additional project tasks such as thermal comfort analysis. Integration and improvement of information flows between BIM and Building Energy Performance Simulation (BEPS) tools has the capacity to help designers assess building performance under various design conditions. In doing so, assessments of building performance and thermal comfort requires additional representative data about indoor environmental conditions and energy consumption. The process of connecting BIM to energy simulation tools, for the explicit purpose of thermal comfort analysis, requires a well-defined Model View Definition (MVD). MVDs define a subset of the Industry Foundation Classes (IFC) schema, which is needed to support a particular business process. This paper develops a MVD for thermal comfort that represents the data needed by building designers or operators to deliver a satisfactory level of thermal comfort in a typical small, single occupant office. The use case consists of a single thermal zone with a HVAC system. The detailed specification for these requirements is based on the IFC data representation. The IfcDoc application tool is used to improve the consistency and define computer-interpretable definition of the MVD. The outputs of this work will allow a standardised exchange of the necessary requirements from BIM to BEPS tools (e.g. EnergyPlus) for thermal comfort analysis.

Keywords–BIM, MVD, BEPS, Thermal comfort, IFC.

I INTRODUCTION

Thermal performance of commercial buildings stock significantly influences comfort and indoor environmental conditions. Improving the thermal performance of the overall building is one of the most effective ways to prevent excessive building energy consumption and to maintain optimal comfortable temperature for occupants. In 2015, the total number of commercial buildings in Ireland was estimated to be around 109,000, and 89% of these buildings were categorised as offices [1]. The energy fraction in Irish office spaces is very high due to maintaining optimal comfort levels through heated buildings, as well as high lighting and equipment consumption and, in some buildings, demand for cooling [1].

Building a complex parametric model for energy simulation can be very challenging for the design team [2]. This is due to the complexity of building geometric designs, as well as their mechanical systems.

A slight design alteration in one building component can have a meaningful impact on the value on the building as a whole. Thus, in practice, value analyses based on new design information need to be performed continually. Therefore, using manual methods of analysing the value of a complex building including their several properties would become; labour-intensive, time-consuming, error-prone and costly [3]. With BIM, a change made to the model automatically updates the drawings, the bill of materials, and the building data.

A BIM is a digital representation and repository of the building data and information. BIM simplifies automated exchange of information in digital format between diverse stakeholders and significantly reduces paper-based document delivery. BIM technology enables a number of automated or semi-automated facility related services such as cost estimates, scheduling, and energy simulation analysis [4]. Improvements to energy efficiency and sustainability, by way of linking the BIM model to Building Energy Performance Simulation (BEPS) tools, allows calculation of energy use during the early design stages [5].

Although BIM provides the ability to simultaneously share multi-disciplinary information within the Architecture, Engineer, Construction, Owner Operator (AECOO) industry, BIM can make simulation models more complex and challenging to the design team, due to the large amount of data contained with the model. This can result in missing essential information, misplaced or distorted building elements during data exchange process between BIM and BEPS tools, which affects the accuracy of analysis results and decisions.

Currently, most integration work between BIM and BEPS has focused on extracting data of building geometry, with a little focused on HVAC system [3]. Moreover, none of the research efforts have particularly focused on extracting BIM data specific to thermal comfort analysis i.e., building objects and its properties.

To address the need and bridge the gaps, the ultimate aim of this paper is to develop a Model View Definition (MVD) for thermal comfort. This MVD represents the data needed by building designers or operators to evaluate and enhance the thermal comfort levels in buildings through simulation tools (e.g. Energy Plus). The role of the MVD defines a subset of the IFC schema, which is needed to perform a simulation.

II State-of-the- art

The most significant design decisions regarding building sustainability are generally made in the preliminary design stages by the architect or the design team [6]. Energy simulation tools are powerful when predicting the energy performance of a given building and the indoor thermal comfort for its occupants [7]. Such tools support the understanding of how a given building should perform under certain conditions and provide the opportunity for the design team to compare it with alternative scenarios.

The accuracy of building energy simulations mainly relies on the user input data, for instance, orientation, weather conditions, building geometry, construction properties, space usage, internal loads, mechanical and HVAC system etc. [8], Fig 1.

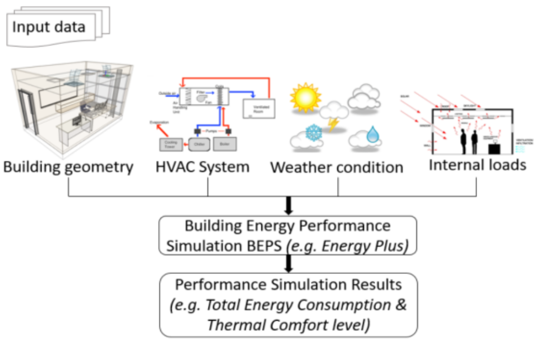

Fig.1 The basic parameters of input data for energy simulation.

There are differences in creating model using the two domains, BIM and energy simulation model. For instance, one of the key variances is the use of the 'Space' entity by BIM and the use of the space entity boundary in energy simulation models. Architectural spaces in BIM such as, rooms, are divided by walls, while in energy simulation models, spaces are referred to as thermal zones and are defined by space boundaries. An integration between these two domains, BIM and energy simulation models can result in a significant saving in energy and cost [8].

BIM technology is mainly centered around interoperability tasks in a common design environment, which supports re-use of information and decreases data duplication between disciplines [9]. However, performing automated or semi-automated energy and indoor environment analysis requires all information relevant to the specific tasks to be clearly defined with the model. This includes a building's objects and its thermal properties, such as the thermal transmittance of the external walls and the number of occupants in a space [10]. Therefore, understanding the level of detail needed for a simulation model is essential for successful integration.

Of the available BIM formats, Industry Foundation Classes (IFC) is the only open life-cycle data model for buildings that is an international standard. Because the IFC data model is so large, only carefully defined subsets of the model are required to support specific business processes. These subsets are called Model View Definitions (MVD), whereby the primary objective of is to ensure standardised import and export of specific requirements for IFC compliant software.

To support this, buildingSMART has developed the IDM/MVD methodology, which is used to define a subset of exchange requirements of the IFC schema. Based on this methodology, buildingSMART released limited types of MVDs, for instance; Coordination View, Reference View and Design Transfer View. However, these MVDs are suitable for variety of workflow, such as Coordination planning, Clash detection and Quantity take-off [11]. Additionally, the mentioned above MVDs are based on a large, complex data structure, but only a small part is needed for specific use cases, in this instance, for analysis of Thermal Comfort performance.

Concept Design BIM (CDB) developed an MVD based on the IFC schema [12]. The scope of this project focused on generating an MVD of energy analysis to support the coordination of energy analysis requirements. In 2013, Holistic Energy Efficiency Simulation and Management of Public Use Facilities (HESMOS) defined exchange requirements for energy analysis. This project did not produce an MVD but rather requirements needed to develop an MVD [13]. However, CDB and HESMOS didn't support thermal comfort analysis requirements. Thus, there is an absence of extraction information to support thermal comfort analysis in commercial buildings.

This work focuses on the development of an MVD for thermal comfort using the IfcDoc application tool. Once BIM software has already implemented this MVD, the output of IFC file will include only the exchange requirements defined for that specific analysis, thus filtering unrelated information.

a) Thermal Comfort

Thermal comfort is a term used to describe occupant satisfaction with their thermal environment [14]. This subject is complex and includes a number of influential factors such as physical, physiological, and psychological factors.

In 1970, Fanger introduced the first thermal comfort model. This model is still in use today, with slight modifications, as defined in ASHRAE Standard 55 [14]. Fanger's model considers five environmental and personal input variables, Fig 2.

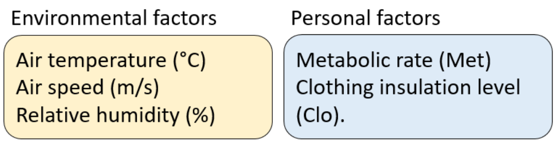

Fig.2 Thermal comfort variables in Fanger's model

Based on Fanger's variables, two metrics commonly used to evaluate comfort performance through simulation are, Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD).

Presently 'adaptive thermal comfort' is the most popular model in use as it is not based on steady state human comfort votes in laboratory conditions [15]. Adaptive models try to account for responsive and behavioural measures, such as opening windows, turning on a fan or adjusting clothing. However, there are still limitations in using the adaptive model [16]. Basically, it can only be used in buildings that adopt passive cooling systems. Also, occupants' metabolic rate should be in the range of 1.0-1.3 met, whilst clothing be within 0.5 to 1.0 Clo. Both the PMV and adaptive models use the top-down approach of statistical analysis, which focuses on average group data.

Thermal comfort is dependent on multiple factors such as indoor environmental conditions, user behaviour, properties of building materials and HVAC systems [17]. Hence, accurate and complete models are needed by the building designer to predict and evaluate thermal comfort levels.

Using BIM as the central data repository for extraction into analysis tools at any time during a buildings' life-cycle to inform decisions can be very effective in improving the thermal comfort levels.

III METHOD FOR BIM-BASED THERMAL COMFORT ANALYSIS

The process approach is divided into two phases, Fig3. Phase 1 deals with definitions of the exchange requirements in order to support automated data exchange from BIM to BEPS for thermal comfort analysis using IFC. This phase is based on IDM/MVD integration and comprises key steps as follows;

A. Business use case (BIM creation)

B. Process Map

C. Exchange requirements

D. Data extraction (MVD).

The next section, provides an overall description for the business use case as well as discusses the data extraction (MVD) in detail. The business use case, process map and the technical specification of the exchange requirements have been detailed in previous work [18]. Phase 2 deals with simulation file generation and thermal comfort analysis that will be presented in the extended future work.

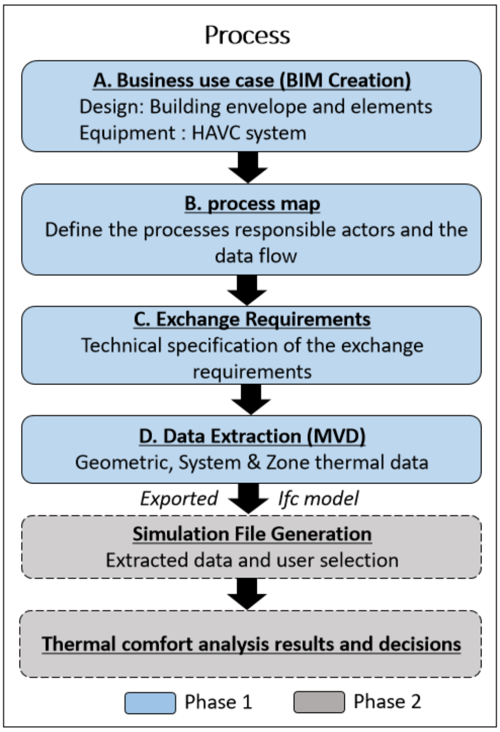

Fig.3 The proposed method for BIM-based thermal comfort analysis.

a) BIM creation

GRAPHISOFT ARCHICAD offers computer aided solutions for manging all common aspects of architectures and engineering during the whole design process of the built environment. ARCHICAD can import and export DWG, DXF and IFC and bcfXML files, among others. In the recent release ARCHICAD 21 there are a variety of useful new features and capabilities ranging from small productivity enhancements to collision detection. ARCHICAD 21 is among the first BIM applications to fully support the IFC 4 open-source standard [19]. Therefore, it is used to model the use case, Fig 4.

The use case was conducted to define the proposed exchange requirements between BIM and BEPS to support thermal comfort analysis. For the initial validation, an existing single thermal zone with HVAC system office and floor area totalling 7m² was modelled. This office is one of the typical offices located in the School of Mechanical & Materials Engineering, University College Dublin.

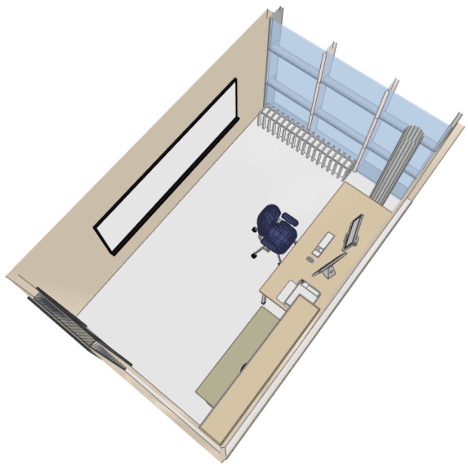

Fig 4: BIM for the use case, a single thermal zone.

The construction details of the model, includes uninsulated concrete and masonry elements, with a single-glazed aluminium frame. The building envelope components consists of concrete block wall, curtain wall, concrete floor and roof, the same as the original office.

Within the use case, additional factors that can influence occupancy comfort were carefully assigned, such as HVAC systems, artificial lights loads, occupant's loads, office equipment's loads and furniture.

Based on the technical specification of the exchange requirements that was defined in the previous work [18]. The next step focuses on specifying all objects and their properties using the IFC4 schema in order to develop the MVD for thermal comfort simulation.

b) Specify the exchange requirements using IFC

This step includes two primary steps: Firstly, identifying entities and property sets in the existing IFC4 schema, that support thermal comfort analysis based on a holistic review of the variables needed for thermal comfort analysis.
Secondly, identifying any missing entities or property from the IFC schema.

The primary IFC element hierarchy is based on the accessing structure,

Project > Sites > Buildings > Stories > Spaces> Elements.

That is, a project at the top-level contains one or more sites. A site is a container of one or more buildings. A building contains one or more stories and a storey is made up of one or more spaces and spaces are defined of one or more elements. If there are building elements directly related to the IfcBuilding (like a wall or curtain wall spanning multiple stories), they are linked with the IfcBuilding by using the objectified relationship IfcRelContainedInSpatialStructure, Fig.5. In this example, both the IfcBuilding and IfcBuildingStorey can have several products contained within structure.

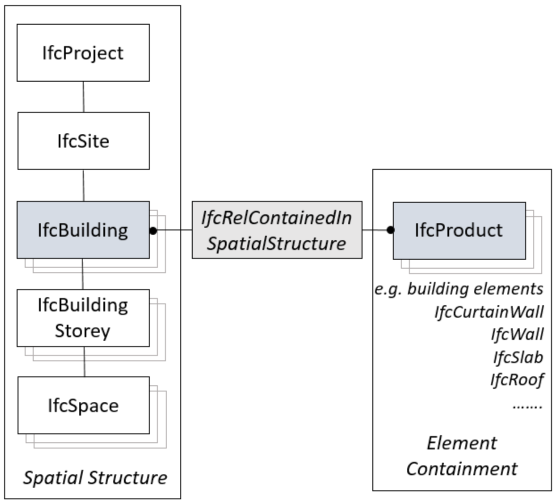

Fig. 5: IfcRelContainedInSpatialStructure, is used to assign elements to a certain level of the spatial project structure.

In order to classify the target information of an existing IFC4 schema, number of sub-steps are required:

(1) Specify IFC entities based on the categories and subcategories to which the elements are appropriate for the business case. The use case for this work has defined 13 objects directly relevant for thermal comfort analysis including: IfcColumn, IfcCurtainwall, IfcDoor, IfcRoof, IfcFurniture, IfcSpaceheater, IfcSpaceBoundary, IfcSlab, IfcSpace, IfcLightFixture, IfcMaterial, IfcWall, and IfcWindow.

This work has also defined another 14 sub-elements which are necessary for establishing the relationships between elements and systems that define levels of decomposition, for example IfcProject, IfcRoot and IfcElement etc.

(2) Identify the attributes associated with each entity's IfcProperty instances, for instance property names and property values.

(3) In an IFC model, building objects (IfcObject) and their properties (IfcProperty) are linked directly by IfcRelDefinesByProperties. In IFC4 IfcRelDefinesByProperties defines the relationships between property set definitions and objects [11]. For instance, a specific property of IfcPropertySet can be related to a specific object of IfcWall through IfcRelDefinesByProperties, Fig 6. This allows for the assignment of one type of property or more for each object. This work has defined over 109 properties relevant for thermal comfort analysis.

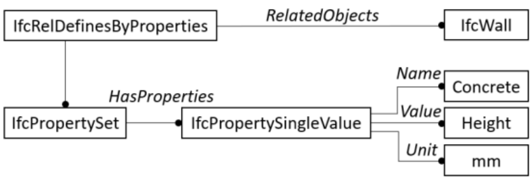

Fig. 6: The relation between (IfcObject) and their properties (IfcProperty).

The recent released IFC schema (IFC4) covers most of necessary information on building objects and their properties needed to fully support thermal comfort analysis. However, the result of identifying the exchange requirements shows that, there is a need to extend the current IFC4 schema to include additional properties. For example, material SolarReflaction and other properties of an IfcMaterial are missing and need to be added, Fig.7. Similarly in IfcLightFixture the properties for Sensible Load and Sensible Load to Radiant need to be added.

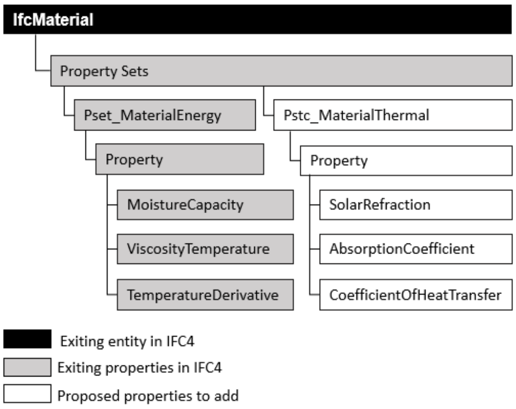

Fig. 7: Proposed properties to add in the IFC4 schema.

It is important to add the missing property sets and properties to the IFC4 of each of the building objects to support more comprehensive analysis. For instance, the property set of Material thermal needs to be added in IfcMaterial to calculate the solar absorption and refraction of building materials. Table 1 summarises a subset proposed to be added properties for IfcMaterial.

Table 1: Proposed a subset to add in IfcMaterial

Name	**Property type**	**Data type**
SolarRefraction	Single-value	IfcReal
CoefficientOfHeatTransfer	Single-value	IfcCoefficientOfHeatTransfer
AbsorptionCoefficient	Single-value	IfcAbsorptionCoefficient

c) Data extraction (MVD).

In the use case, two main entities related to thermal comfort performance through simulation have been defined to model physical information in the IFC standard, Fig 8, namely:

- "IfcElement".
- "IfcSpatialStructureElement"

The "IfcElement" is the upper classification for concepts describing all property sets for the major functional parts of a building. Examples are Building structure elements (foundation, floor, roof, wall etc. and its materials), Distribution elements (including heating, ventilation, air conditioning, electrical and equipment elements) and Furnishing elements (desk, chair etc.), Fig 9.

The "IfcSpatialStructureElement" is the upper classification for concepts that define the spatial structure of an IFC standard file, including "IfcSpace". The "IfcSpace" describes the all property sets for a space (e.g. volume, number of person, activity assigned within space, dry bulb temperature, relative humidity, etc.).

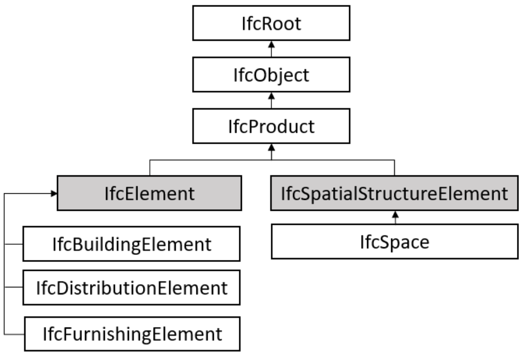

Fig 8: The main entities have been defined which are related to thermal comfort performance through simulation.

After defining all requirements related to thermal comfort performance, the data is stored in the proposed IFC model, such as data for geometry, HVAC system and materials properties etc. In this use case, a total of 27 objects items and over 109 properties relevant for thermal comfort analysis were defined.

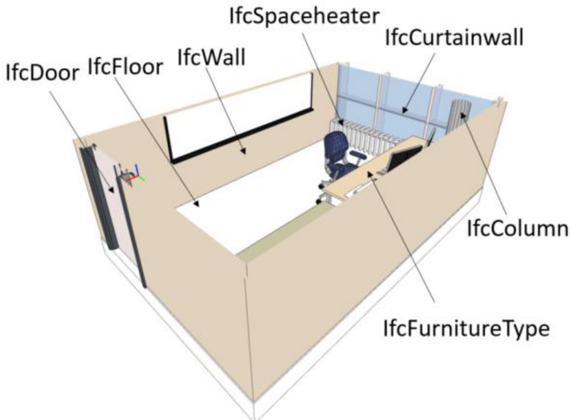

Fig 9: Objects of "IfcElement", includes the elements of building, distribution and furnishing.

To improve the consistent and computer-interpretable definition of the MVD as true subsets of the IFC specification with enhanced definition of concepts, the IfcDoc tool is used to generate MVD documentation, Fig 10. The role of the proposed MVD defines a subset of the IFC schema, which is required to perform thermal comfort performance through simulation for commercial office spaces.

d) IFC Documentation Generator (IfcDoc)

The IFC Documentation Generator (IfcDoc) tool is a free tool developed by buildingSMART International. The main objective of this tool is to enable documentation of the IFC MVD by generating diagrams, schema definition, indices and contents of the user specification [20]. Furthermore, the IfcDoc tool can also provide limited validation of MVDs and ensure consistent and computer interpretable definitions, via mvdXML export functionality.

The starting point when creating the MVD that underlies IFC schema specification is to load a baseline file containing multiple Exchange Definitions. In this case IFC4 Addendum 2 has been loaded. Usually, this baseline includes MVD definitions of Reference View and Design Transfer View.

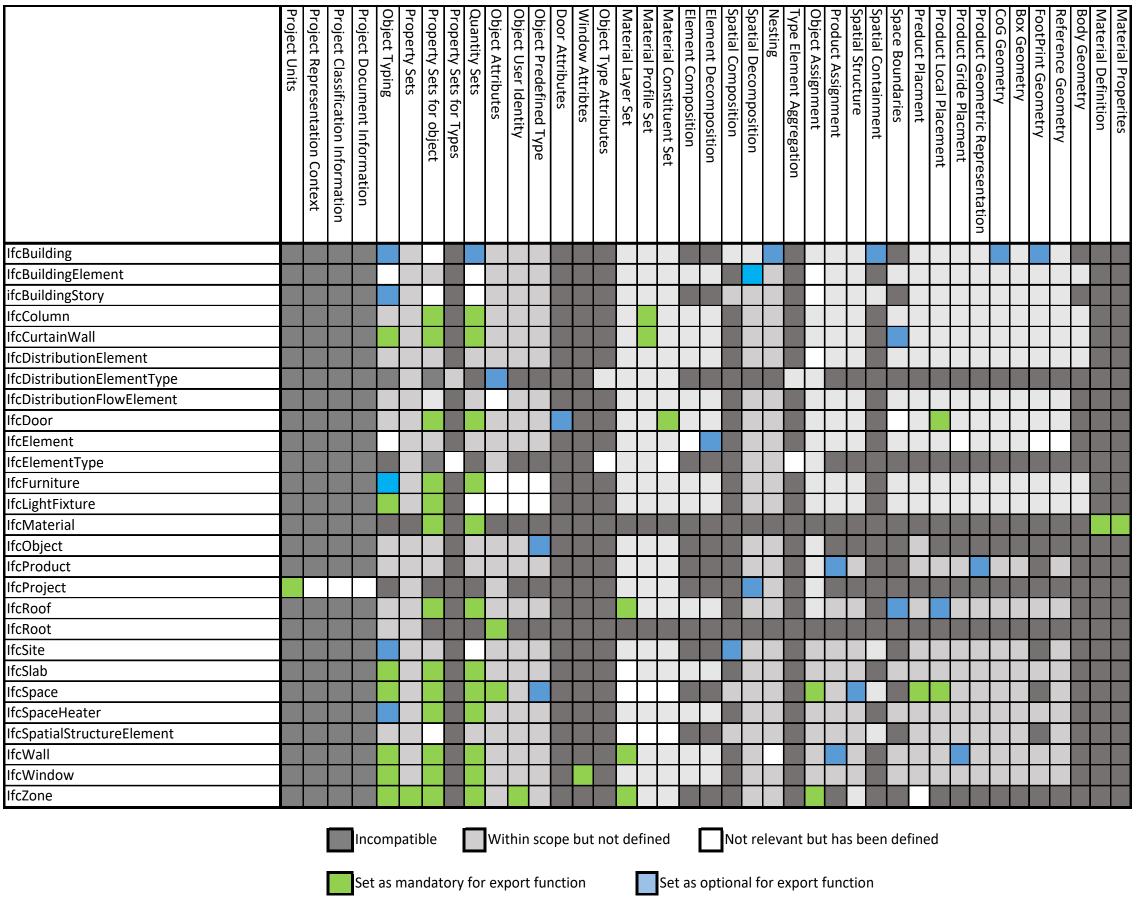

Fig 10: Subset of the exchange requirements for thermal comfort performance analysis

Once the schema has been loaded, the hierarchy is displayed and populated with the IFC schema definitions for the specific IFC release.

All information defined previously in the IDM can be linked to the MVD definition. Fig 10 illustrates two types of rules on the IfcDoc interface; 1. A structure and 2. A constraint. The first rule is used to valued relationships and references, while the second is used for validating properties and specific values. For instance, users can specify that IfcWall must have attributes for Name, ObjectType and MaterialsConstituents, in order to make the full connection enclosure.

VI Results and Discussion

The presented MVD provides a reproducible transformation between BIM and thermal comfort evaluation models, as contained within the EnergyPlus simulation engine. The outcome of this process is a formal representation of the data and information required to be in BIM in order to support such modelling and analysis activities (Fig.10).

The case study demonstrates how different requirements can be adopted consistently to produce a design model customised for each analysis. However, the presented MVD only addresses thermal comfort issues and is limited to the current IFC release, IFC4.

The IFC schema intentionally contains definitions across all disciplines and life-cycle phases. For a reliable data exchange, however, the current IFC release still needs to be expanded to provide additional data related to building materials and their thermal properties.

For automated interactions between these tools to occur, the information transmission must be categorised in a standard manner to avoid disjunction between architectural and thermal engineering data and to enhance workflow. This is only possible through standardised information property sets for information exchange between the two domains, which ensures consistency.

VII Conclusions AND FUTURE WORK

The paper contributes to the development of a MVD for thermal comfort analysis. The role of the MVD is to define building design information from an IFC based BIM in order to support automated information exchange between BIM and BEPS tools. MVD compliant output of IFC files from BIM-based CAD tools includes only the exchange requirements defined for that specific analysis, thus filtering unrelated information.

Using BIM as a data source for establishing a thermal simulation model can be complex and challenging for a design team due to the large amount of data it contains. The results of this work will assist in resolving these complexities and improving automated or semi-automated information flow.

To date, research efforts have failed to focus on automated extraction of BIM information specifically for support of thermal comfort performance analysis. The MVD developed in this study is the first step in enabling rich and comprehensive data exchange for building objects and their properties. The MVD enhances the quality of BIM data, which will reduce the loss of information when exchanging BIM files, particularly when evaluating thermal comfort performance through simulation. Consequently, thermal comfort analysis is conducted with high accuracy and efficiency.

The present MVD contributes to environmental and energy building efficiency studies. It can assist the AECOO industry on a global scale by advancing traditional workflows for thermal comfort analysis.

The next phase of this research will focus on extension of the MVD to account for CFD based simulations of thermal comfort. After completion, the proposed MVD will be submitted to BuildingSMART international group for acceptance and publication as an official Model View Definition (MVD) for thermal comfort analysis.

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